EFFECTIVE 3D GEOMETRY EXTRACTION AND REVERSE CAD MODELING

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INTRODUCTION

The goal of this work is to develop and implement a technology capability for providing cost-effective and rapid geometry evaluation of parts and processes. We were motivated by the new availability of fully three dimensional nondestructive CT scanning for a variety of manufactured parts and assemblies on a rapid and cost-effective basis, with resolutions commensurate with the tolerances required for a variety of manufacturing processes. High-speed, high-quality three dimensional scanning can be accomplished on a overnight service basis for a variety of objects, for costs ranging from a few hundreds to a few thousands of dollars. The resulting images contain quantitative information relating the local x-ray density of scanned objects at every voxel in a three dimensional raster space. There have been significant advances in methods for quantitative volumetric processing and information extraction from these images. However, for many manufacturing process verification applications, the resulting three dimensional images contain more information than can be effectively handled by many end users, particularly when the size of the 3D image data files (often larger than 1 Gbyte) is considered.

To exploit this new nondestructive 3D imaging capability, we are developing a general purpose suite of capabilities for reducing the volume of information in these 3D images and concentrating it into a form and format that is directly usable by a design and manufacturing engineers, and that can be tailored to provide timely and reasonably priced solutions to a variety of manufacturing process verification application needs. Providing the results of 3D geometry characterization of actual manufactured and prototype parts directly in CAD-package formats allows for much faster development cycles, by reducing the time needed to utilize first-part inspection results, and also enables the rapid re-engineering of product designs and refinement of manufacturing processes when appropriate.

Our approach has been to integrate both newly available state-of-the-art and off-the-shelf technology capabilities for 3D surface boundary measurement and for 3D geometry extraction and enhancement with existing CAD tools to facilitate accessibility of the tremendous amounts of information contained in 3D images of scanned parts and assemblies.

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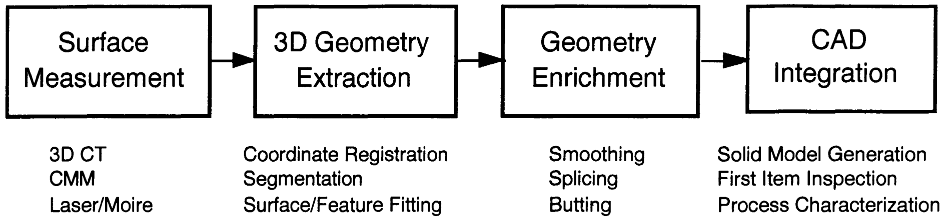

Figure 1. Reverse CAD For Manufactured Parts. Nondestructive capture of an object's full 3D geometry can be described as a four step process. For many applications, all four steps are not required, resulting in cost reductions and/or a reduction in the time needed to solve a particular application.

3D GEOMETRY CAPTURE AND REVERSE CAD MODELING

Conceptually, the overall process of verifying 3D geometry of a particular part can be broken down into four basic tasks, as shown in Figure 1.

Measurement of the x-y-z locations of large numbers of surface boundary points can be accomplished in a variety of ways, including 3D CT scanning followed by extraction of the boundary points from the 3D image, use of optical surface scanners, and modern coordinate measuring machines. Each of these methods have certain strengths and weaknesses, making the optimal choice of boundary measurement technique depend strongly on the requirements of each particular application. For instance, 3D CT scanning results in both exterior and interior surface measurements, but imposes some limitations on both the overall size and composition of the object to be scanned. CMM machines can provide exquisite accuracy and precision to sub-mil levels, but are relatively slow and often difficult to program and operate.

Effective extraction of 3D geometry is made possible by the recent advent of commercially available software for real-time interactive visualization, manipulation, segmentation, and fitting of 3D CAD-style geometry to large sets or "clouds" of x-y-z object boundary points. One example is the Surfacer package from Imageware, Inc. of Ann Arbor, MI, that provides the responsiveness and control necessary to understand the important features of an object and to inject an appropriate amount of engineering judgment into the process of concentrating the relevant information from a 3D image into a standard CAD format. At this stage, huge reductions in the file sizes that must be dealt with are possible. For instance, a 3D-CT image can be Gigabytes in size, while the corresponding boundary point set file length is typically measured in Megabytes for complex parts, and the corresponding CAD-format files describing the geometry are typically only tens of kilobytes long.

Geometry enhancement and repair steps can be accomplished through a variety of either interactive or semi-automated tools. Operations such as joining, splicing, butting, and smoothing of fitted geometry allow further control of the degree to which the description of measured geometry is constrained to the that of the nominal part design. These operations also allow further interjection of engineering judgment into a particular problem, for instance by requiring that a cylindrical feature be described as a true cylinder instead of as an arbitrarily shaped surface.

CAD integration typically involves simply importing the fitted geometry description into the desired CAD system, either using the appropriate native CAD format or via a common standard such as IGES. For many applications, the surface geometry is then converted into a solid model, and can be converted into a parameterized description as needed. Once the geometry description is in the CAD system, all of the power of the commercial CAD tools can be brought to use by the end customer for a variety of tasks, such as generation of inspection drawings, dimensional comparisons between the actual part and its original design model.

ADVANTAGES OF FULLY VOLUMETRIC METHODS

Many of the well-known advantages of solid modeling that are driving CAD users toward its use certainly apply to the process of 3D geometry extraction as well. In addition, there are several additional gains to be made by employing fully volumetric tools to the process of defining Reverse CAD geometry for manufactured parts and prototypes.

By avoiding the common multifaceted planar approximations commonly used for visualization and for rapid prototyping purposes, all of the ambiguities inherent in the edge and surface definitions at the polygon boundaries can be avoided, resulting in a significant increase in the accuracy of an object's geometrical definition. The common tradeoff between the sizes and numbers of polygons used, and its often empirically based determinations of loss of geometrical accuracy, is also completely avoided. From a practical standpoint, we find that the large numbers of polygons (often in the millions) needed to adequately represent the surfaces of complex manufactured shapes simply choke up many CAD systems which are nominally capable of handling this type of file format.

From a surface measurement viewpoint, there are also advantages to using fully volumetric methods. The enhanced accuracy and unambiguity of the 3D coordinate registration process can often eliminate the need to fabricate precision inspection fixturing, a process that is often slow and extremely expensive: the design and manufacturing of fixturing can often cost more and take longer than the actual inspection of single part types, making precise evaluation of prototypes impractical. For the 3D CT method of surface measurement in particular, using volumetric processing to extract boundary geometry also provides a means to avoid the confusion or interference possible when the CT sectioning plane axis follow certain 3D geometrical features, such as the tops and bottoms of cylinders with long axis parallel to the sectioning planes or semi-planar surfaces approximately parallel to the CT sections, which typically produces a poor sampling of the surface geometry when strictly 2D methods of image boundary extraction are used.

EXAMPLE OF THE 3D REVERSE CAD PROCESS

We recently demonstrated this new capability on a part which had undergone design modifications during the manufacturing process. This plastic injection-molded part, approximately 2.5" tall by 1" diameter, was originally designed using a commercial CAD solid modeling package, but the modifications made subsequently had not been incorporated back into the design modeling database.

Using the tools described in this paper, we were able to extract the boundary point measurements from an unfixtured 3D x-ray CT image of the actual part, register the point measurement set to the coordinate system used in the CAD design model, compare the measurements of the final part to the model, find and characterize the geometry of the changes, and incorporate those changes back into the original CAD model with only a few days of effort. The voxel size of the 3D image was 0.005" (5 mils), and the final fitted surface geometry had average absolute errors of less than 1/2 that dimension, even after symmetry conditions were imposed. The results are illustrated in Figure 2.

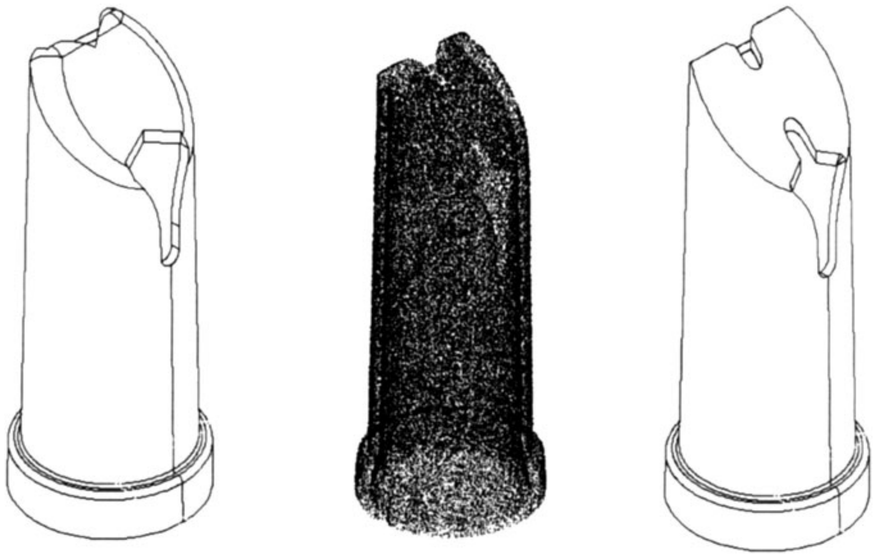

Figure 2. Reverse CAD Demonstration. At left is a view of the original CAD model of a molded plastic part. At center, the surface boundary point set of the actual manufactured part obtained from 3D CT imaging, showing both internal and external surfaces. At right, the modified CAD model showing incorporation of the changed features. The average accuracy (0.0023") of the modified model as compared to the measured surface points was less than 1/2 the voxel size in the original 3D-CT image (0.005").

Another, more complicated example that we recently completed is the generation of a Reverse CAD model for a hollow-cast turbine blade. These parts are hollow cast from a nickel-based super-alloy, and is contained in a rectangular envelope approximately 3" tall by 2" wide by 1" thick. This particular part was designed some time ago using conventional 2D drawing based, so no 3D CAD design model existed. The blade was examined using 3D-CT methods in just a few hours, without any special fixturing to mount the part in the CT scanner, to produce a complete volumetric map of part density. Using the methods described above, the coordinates of the surface boundaries were extracted to yield a set of approximately 750,000 x-y-z triples. These points then were interactively registered to the coordinate system used in the original drawings. Next, using the interactive tools described above, the point set was segregated into groups corresponding to the interior and exterior surfaces. These groups were further divided into sub-groups corresponding to simple geometrical entities such as planes, boundary curves, and simply-curved surfaces. The sub-groups were then fitted with CAD-style geometrical entities, and those entities were appropriately combined and stitched together into a "water-tight" description of the interior and exterior surface geometries. The results for the interior cooling passages are shown in Figure 3.

To create a solid CAD model, these geometry descriptions were imported into a common 3D CAD package (Unigraphics by EDS, Inc.). First the exterior surfaces were stitched into a solid description of the outer part envelope. The interior surfaces were stitched into a solid "tool" that was used to remove the interior passages from the part envelope, resulting in a full solid model of the as-manufactured part.

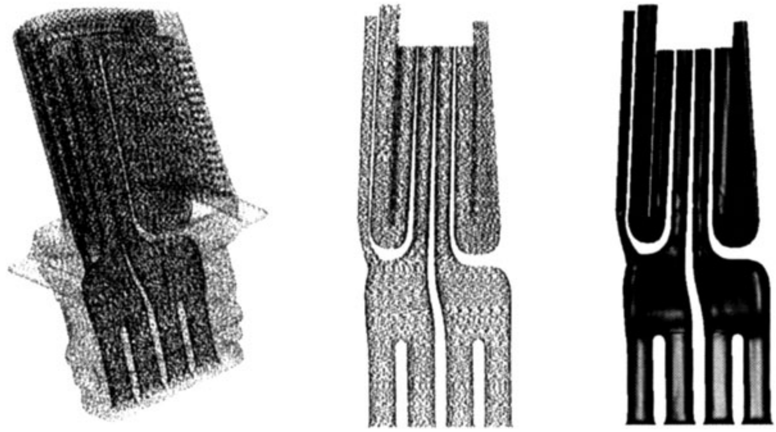

Figure 3. Reverse CAD Modeling of Turbine Blade. At left, boundary points of a hollow-cast turbine blade extracted from a 3D-CT image of the part. At center, the points corresponding to surfaces of the interior cooling passages only were interactively selected. At right, a rendering of the CAD-style surfaces that were fitted to the interior surface points.

RAPID ACCESS TO SERVICES

We envision that in the future, a variety of manufacturers will utilize services such as the part geometry measurement, but that they will have neither the business drivers nor the technical expertise to effectively implement their own internal capabilities. Thus, we anticipate that a business niche will exist for providers of these services, especially to smaller or more specialized concerns. However, to be successful these service providers will have to make their services available in extremely rapid fashion and at correspondingly low price levels. We expect that use of computer networks or the so-called "Information Superhighway" will be an effective way to rapidly move information about parts and processes between groups of specialized service providers and their customers.

We are already making use of computer networks to link geographically separated organizations. Overnight shipping services can already rapidly deliver physical parts from manufacturers to scanning service shops, such as the x-ray CT group at GE Aircraft Engines. We have already demonstrated that parts can be shipped from a manufacturing site to an imaging facility, a full 3D CT image collected, and the resulting image data delivered over computer networks to an analysis site for geometry extraction or reverse CAD modeling in times as short as 36 hours.

We also have recently made generally available a preliminary hypertext guide to this and other related manufacturing process and design engineering tools that are generally available at GE. This guide is openly available over the World-Wide Web, a service that is accessible over the Internet using freely distributed software (e.g., Mosaic) on most popular computer platforms. This information guide to manufacturing services can be found at the URL address http://ce-toolkit.crd.ge.com. The guide contains hyperlinked text and graphics describing several example projects that we have successfully completed. We have also implemented a conventional electronic mail server at address services@ce-toolkit.crd.ge.com for those without direct Internet access.

CURRENT STATUS AND FUTURE APPLICATIONS

We have successfully performed services for a variety of dimensional verification, geometry extraction, and reverse CAD applications, and we are now actively seeking new applications for this technology. We believe that this new capability can significantly decrease the time and costs associated with a variety of manufacturing tasks, including development of 3D design models for existing parts, rapid re-engineering, modification of current designs, and the capture of design changes and manufacturing "know-how" into design databases. In the future, we anticipate that these tools will also have application in areas including process monitoring and control, new process development and verification, process trend and machine tool wear characterization, and manufacturing configuration control.

By rapidly converting the information from 3D geometry verification inspections into the "native language" of the CAD tools routinely used by engineers and designers, we provide access to answers for the specific questions they deem relevant, without requiring them to become facile with the sorts of tools the 3D NDE community currently favors. Since the measurement techniques used are nondestructive, this process is particularly well suited to evaluation of prototypes that are valuable or difficult to replace, or that require additional destructive evaluations to characterize mechanical or material properties, as well as for applications that require iterative adjustment of geometry-affecting processes.

The ability to bring these rapid, powerful, and cost effective capabilities to bear on these manufacturing problems should ultimately provide cost take-outs for process development, cycle time reductions in new product design/tooling/manufacturing, added flexibility in vendor interactions, and enable faster response to changing market conditions for a wide variety of manufacturing businesses.